Precambrian Research, 56 (1992) 33–49
Elsevier Science Publishers B.V., Amsterdam

CONTRIBUTION
SERIES
92-001

Geochemistry of mineralized and barren, Late Proterozoic felsic volcanic rocks in southeastern Cape Breton Island, Nova Scotia (Canada)

J.Dostal[a], J.D. Keppie[b] and M. Zhai[a]

[a]*Department of Geology, Saint Mary's University, Halifax, N.S. B3H 3C3, Canada*
[b]*Nova Scotia Department of Mines and Energy, P.O. Box 1087, Halifax, N.S. B3J 2X1, Canada*

(Received January 5, 1991; accepted after revision August 21, 1991)

ABSTRACT

Dostal, J., Keppie, J.D. and Zhai, M., 1992. Geochemistry of mineralized and barren, Late Proterozoic felsic volcanic rocks in southeastern Cape Breton Island, Nova Scotia (Canada). Precambrian Res., 56: 33–49.

Late Proterozoic volcanic rocks of southeastern Cape Breton Island, Nova Scotia (Canada), comprise part of the Avalon Composite Terrane of the Canadian Appalachians. They occur in several fault blocks (from southeast to northwest: Coastal, Stirling, East Bay Hills and Coxheath). The blocks are composed mainly of Late Proterozoic volcanic suites which are predominantly bimodal and were emplaced in a volcanic arc setting. The basaltic rocks range from tholeiitic (Coastal and Stirling) to calc-alkalic (East Bay Hills and Coxheath). The felsic volcanic rocks of the Stirling block host a massive sulphide deposit but no economic mineralization has been discovered in the volcanic rocks of the other blocks.

The felsic volcanic rocks display significant differences in composition amongst the fault blocks. The Coastal and Stirling blocks contain low-K rhyolites with low abundances of strongly incompatible trace elements and relatively flat chondrite-normalized REE patterns. These rocks were probably derived by the melting of mafic igneous rocks compositionally similar to tholeiitic basalts of Archean greenstone belts or island arc tholeiites. Compared to the Coastal block rocks, the Stirling rhyolites are depleted in Eu, Sr and Al_2O_3 indicating extensive feldspar fractionation. Trace element characteristics of the Stirling block rhyolites are closely comparable to those of the Archean felsic metavolcanic rocks from the Superior Province of the Canadian Shield which are preferentially associated with massive sulphide mineralizations. The similarities suggest that the low-K felsic volcanic rocks with flattish REE patterns and negative Eu and Sr anomalies are also indicative of a promising environment for massive base-metal sulphide mineralization in volcanic belts at least as young as Late Proterozoic. The rhyolites of the Coxheath block have calc-alkalic affinities, higher contents of strongly incompatible elements than the Coastal and Stirling rhyolites and their REE patterns are enriched in light REE. The East Bay Hills felsic tuffs resemble the Coxheath rhyolites. They both could be derived by melting of a source with a composition of the average lower crust.

Introduction

Many Archean massive base-metal sulphide deposits are associated with volcanic rocks and several studies have suggested that the felsic volcanic rocks from ore-bearing horizons have a distinct rare-earth element (REE) distribution of use in mineral exploration (e.g. Campbell et al., 1982, 1984; Lesher et al., 1986). However, it is not evident whether similar criteria can be also extended to post-Archean rocks (e.g. Strong, 1984). In order to test this option, the study focused on the distribution of trace elements in Late Proterozoic felsic volcanic rocks from southeastern Cape Breton Island, Nova Scotia (Canada), some of which are associated with the Mindamar (Stirling) base-metal deposit (Fig. 1).

The volcanic rocks occur in several belts/fault blocks, which are part of the Avalon Composite Terrane of the Canadian Appalachians (Keppie, 1989). The volcanic se-

0301-9268/92/$05.00 © 1992 Elsevier Science Publishers B.V. All rights reserved.

93-01703/

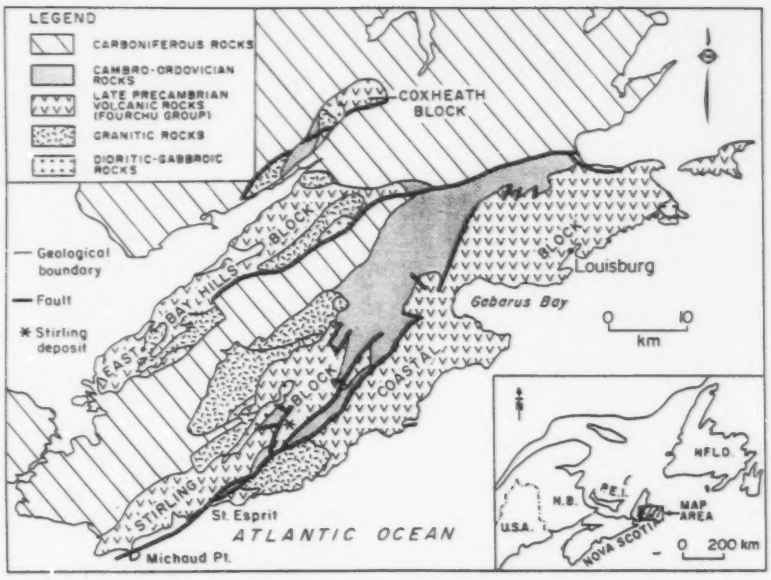

Fig. 1. Geological map of southeastern Cape Breton Island, Nova Scotia.

quences are predominantly bimodal and were emplaced in a volcanic arc setting (Dostal et al., 1990). The purpose of this study is to: (a) compare the composition of the felsic volcanic rocks of the massive sulphide deposit-bearing Stirling fault block with Archean ore-bearing rhyolitic rocks in the Superior Province of the Canadian Shield, and with similar rocks of the other blocks from southeastern Cape Breton Island that are not associated with known massive sulphide deposits, and (b) place constraints on their petrogenesis.

Geological setting

The Avalon Zone is a composite terrane amalgamated during the latest Proterozoic that extends along the southeastern margin of the Appalachians from the Avalon Peninsula of southeastern Newfoundland through Nova Scotia and New Brunswick to eastern Massachusetts, for a distance of about 1500 km (Keppie, 1989). The zone includes a Middle Proterozoic metamorphic basement (gneisses and amphibolites) that is in tectonic contact with platformal metasedimentary rocks of Late Middle Proterozoic age. These rocks are, in turn, overlain by Late Proterozoic sequences containing significant amounts of volcanic rocks ~570–680 Ma old. In Cape Breton Island, these volcanic rocks were assigned by Weeks (1954) to the Fourchu Group, which has since been informally subdivided by Barr et al. (1989) who have suggested that rocks at the northeastern end of the Coastal block (Fig. 1) may grade upwards into the Lower Cambrian. The Late Proterozoic strata are unconformably overlain by Cambrian–Ordovician sequences containing Acado–Baltic trilobite fauna.

The Late Proterozoic volcanic rocks in southeastern Cape Breton Island occur in several fault blocks from the southeast to the northwest: Coastal, Stirling, East Bay Hills and Coxheath (Fig. 1). The blocks are each composed of a suite of volcanic and subordinate sedimentary rocks invaded by a variety of intrusive bodies. The volcanic units consist of pyroclastic rocks and subordinate lava flows intruded by dikes, sills and other minor intru-

sive bodies, which, in the Coastal block were interpreted to be feeders for the volcanic pile. In the flows and cogenetic sheets, the mafic and felsic types strongly predominate over intermediate rocks. The volcanic rocks are subaerial except in the Stirling block where they are largely submarine. The sedimentary rocks of the Stirling block consist of turbidites and chemical sedimentary deposits. The rocks on the Michaud Point Peninsula (Fig. 1) are separated from the other outcrops of the Fourchu Group probably by a large fault and it is not clear how they are related to the other blocks. The volcanic rocks of the Fourchu Group have yielded concordant U–Pb zircon ages of: (1) 574 ± 1 Ma in the Coastal block; (2) 676 ± 1 Ma in the Stirling block; and (3) ~600–660 Ma in the East Bay Hills block (Barr et al., 1990). The Coxheath block rhyolites were inferred to be synchronous with cross-cutting plutonic rocks and these yielded $^{40}Ar/^{39}Ar$ hornblende plateau ages between 600 and 635 Ma (Keppie et al., 1990). The mafic rocks of the Fourchu Group have a chemical composition typical of the volcanic arc sequences and range from tholeiitic in the Coastal and Stirling blocks to calc-alkalic in the East Bay Hills and Coxheath blocks (Dostal et al., 1990).

The only known massive sulphide deposit in southeastern Cape Breton Island (Mindamar deposit) is located in the Stirling block. The deposit rests conformably between felsic lavas and overlying intermediate pyroclastic rocks and is considered to be of syngenetic hydrothermal origin formed in a subaqueous environment (Richardson, 1953; Watson, 1954; Miller, 1979). A mine was in operation until 1956 and produced approximately one million tons of ore averaging 6.4% Zn, 1.5% Pb and 0.74% Cu (Miller, 1979).

Petrographic notes

The felsic lavas and sheets of the Fourchu Group are variably massive, flow banded/laminated or spherulitic and are generally porphyritic with quartz and/or feldspar phenocrysts. The phenocrysts are enclosed in a groundmass composed of quartz and feldspars with a minor amount of sericite, chlorite, epidote and opaques. Carbonates usually occur as isolated blebs or veinlets. Compared to rhyodacites, rhyolites have less plagioclase and more quartz in their mode and contain variable amounts of K-feldspar. Associated felsic tuffs vary in their proportions of crystals, glass and lithic fragments, and both welded and unwelded varieties occur. The crystals are mainly plagioclase with some alkali feldspar and quartz. Pumice and devitrified glass shards are occasionally preserved. Lithic fragments are commonly dacitic or rhyolitic in composition. The Fourchu Group rocks in the four fault blocks contain mineral assemblages consistent with sub-greenschist- to greenschist-facies regional metamorphism.

Sampling and analytical notes

Most felsic volcanic samples were collected in the Stirling block from drill cores. The samples from the Coastal block were mostly collected along the shore of Gabarus Bay. Samples from the Coxheath block are from inland outcrops and quarries whereas samples from the East Bay Hills block are from roadcuts. A few samples were also collected from Michaud Point.

Analyzed rocks from Coastal, Stirling and Coxheath blocks are lavas and sheets (except the tuff samples from a drill hole of the Stirling block located at St. Esprit). On the other hand, the samples from the East Bay Hills block and Michaud Point are mostly pyroclastics; analyzed tuffs contain only minor amounts of visible foreign material. The average composition of the least altered rhyolitic rocks of the Coastal, Stirling and Coxheath blocks are given in Table 1 together with the averages for the East Bay Hills and Michaud Point felsic volcanic rocks. Selected analyses of the rhyolitic

TABLE 1

Average composition of felsic volcanic rocks of the Fourchu Group

	Coastal block		Stirling block		Coxheath block		E. Bay block		Michaud Point	
$n=$	17		15		12		6		7	
wt%										
SiO_2	73.30	(1.92)	76.54	(1.90)	74.12	(2.62)	70.94	(4.26)	75.07	(1.55)
TiO_2	0.40	(0.14)	0.26	(0.05)	0.37	(0.12)	0.43	(0.23)	0.23	(0.05)
Al_2O_3	14.04	(0.88)	11.95	(1.03)	14.20	(1.39)	14.98	(1.27)	13.74	(0.52)
Fe_2O_3	2.83	(0.61)	2.75	(0.79)	2.27	(0.71)	2.77	(1.25)	1.51	(0.56)
MnO	0.21	(0.15)	0.06	(0.03)	0.05	(0.03)	0.06	(0.02)	0.14	(0.10)
MgO	0.83	(0.42)	1.31	(0.43)	0.82	(0.20)	1.08	(0.70)	0.35	(0.27)
CaO	1.64	(0.77)	1.60	(0.82)	1.01	(0.73)	1.72	(1.31)	0.98	(0.82)
Na_2O	5.17	(0.86)	4.27	(1.02)	4.01	(0.79)	4.26	(1.24)	5.19	(0.36)
K_2O	1.50	(0.77)	1.22	(0.64)	3.08	(1.07)	3.65	(0.77)	2.75	(0.53)
P_2O_5	0.08	(0.04)	0.04	(0.01)	0.07	(0.03)	0.11	(0.07)	0.04	(0.01)
ppm										
Rb	30	(19)	29	(19)	104	(40)	136	(47)	51	(18)
Sr	188	(98)	65	(28)	135	(70)	137	(64)	148	(79)
Ba	402	(143)	190	(94)	500	(224)	648	(342)	753	(77)
Zr	162	(26)	130	(21)	223	(62)	177	(58)	153	(9)
Y	36	(13)	28	(8)	34	(6)	31	(14)	26	(4)
Nb	6	(1)	5	(1)	11	(1)	11	(2)	9	(2)
V	16	(13)	12	(16)	23	(15)	52	(48)	16	(13)
Cr	9	(8)	4	(4)	8	(8)	17	(13)	7	(6)
Ni	7	(4)	5	(4)	11	(4)	18	(9)	4	(2)
Zn	60	(32)	61	(54)	42	(9)	50	(12)	55	(78)
$n=$	5		11		4		4		3	
Sc	13.1	(1.8)	9.79	(2.13)	5.80	(2.33)	8.18	(3.47)	4.63	(1.25)
Hf	4.91	(0.22)	3.45	(0.54)	6.72	(2.26)	4.22	(0.74)	3.50	(1.13)
Th	2.85	(0.57)	2.45	(0.52)	15.4	(2.5)	16.7	(5.9)	7.73	(0.55)
La	16.0	(1.6)	7.90	(1.58)	25.7	(4.6)	21.3	(3.4)	23.2	(4.6)
Ce	40.9	(4.3)	19.5	(3.7)	59.5	(12.8)	48.4	(9.8)	53.8	(11.8)
Sm	6.62	(1.08)	3.12	(0.67)	5.51	(0.48)	4.52	(1.30)	4.11	(0.82)
Eu	1.75	(0.30)	0.82	(0.24)	0.97	(0.03)	0.99	(0.34)	0.97	(0.05)
Tb	1.33	(0.25)	0.73	(0.19)	0.99	(0.07)	0.62	(0.23)	0.60	(0.12)
Yb	5.51	(0.97)	3.35	(0.85)	3.97	(0.53)	2.22	(1.11)	2.71	(0.66)
Lu	0.86	(0.13)	0.53	(0.13)	0.60	(0.10)	0.34	(0.17)	0.44	(0.10)

Values in brackets correspond to 1 standard deviation; n=number of samples. The averages for the Coastal, Stirling and Coxheath blocks include only the rhyolitic lavas and related sheets. The East Bay Hills and Michaud Point's averages include mainly tuffs.

rocks and tuffs are reported in Tables 1, 2 and 3*.

Major elements and Rb, Sr, Ba, Zr, Nb, Y, Ni, Cr, V and Zn were determined by X-ray fluorescence, whereas REE, Hf, Th, Cr and Sc were analyzed by the instrumental neutron activation technique. The analytical error of the trace element determinations is less than 10%.

Geochemistry

The volcanic and subvolcanic rocks of the Fourchu Group are predominantly bimodal. Intermediate rocks with SiO_2 contents in the

*The complete set of the analyses can be obtained on request, from the authors.

TABLE 2

Selected analyses of felsic volcanic rocks from the Stirling block

	Lavas and sheets													Tuffs				
	4-120	4-289	4-345	3-293	3-400	3-359	3-570	3-587	2-270	2-325	2-386	1-54	1-113	2-170	2-336	2-417	2-447	2-457
wt%																		
SiO_2	74.07	75.65	76.37	78.07	77.92	74.91	72.67	77.59	71.23	73.88	76.65	69.86	71.19	75.56	77.15	76.00	77.70	84.64
TiO_2	0.33	0.27	0.27	0.22	0.22	0.20	0.19	0.17	0.29	0.30	0.26	0.29	0.29	0.30	0.13	0.13	0.12	0.11
Al_2O_3	13.03	9.47	10.95	11.25	11.22	11.16	10.88	10.99	13.43	13.10	12.07	11.62	12.20	10.12	11.39	10.98	10.25	8.60
Fe_2O_3	2.45	2.82	2.15	1.44	2.25	2.36	3.29	2.23	3.37	3.26	2.20	4.60	3.17	3.65	2.20	2.06	1.72	0.77
MnO	0.02	0.05	0.02	0.04	0.04	0.10	0.07	0.03	0.06	0.06	0.05	0.08	0.06	0.08	0.12	0.09	0.12	0.07
MgO	0.68	1.43	0.82	0.91	0.80	1.11	5.05	1.97	1.46	1.73	1.06	2.53	1.89	1.90	2.57	2.12	1.62	0.93
CaO	1.01	2.41	2.08	1.07	1.60	2.16	0.82	0.54	1.90	0.57	1.60	3.95	3.28	1.58	0.39	1.49	1.43	0.76
Na_2O	4.76	2.47	3.01	5.31	3.21	5.24	3.74	5.41	3.99	5.28	3.82	2.16	3.48	1.65	0.73	1.14	4.70	4.45
K_2O	1.41	1.58	1.76	0.80	1.31	0.33	0.28	0.35	2.14	0.80	1.98	0.86	1.09	1.49	3.25	3.37	1.02	0.20
P_2O_5	0.08	0.03	0.05	0.03	0.04	0.03	0.03	0.03	0.05	0.06	0.04	0.05	0.05	0.07	0.02	0.02	0.02	0.02
LOI	2.10	3.70	2.30	1.30	2.00	2.30	3.40	1.20	2.50	0.90	1.70	5.00	3.80	4.40	2.70	3.60	2.40	0.80
Total	99.94	99.88	99.78	100.44	100.61	99.90	100.42	100.51	100.42	99.94	101.43	101.00	100.50	100.80	100.65	101.00	101.10	101.35
ppm																		
Rb	39	46	51	19	32	8	6	2	51	16	61	20	25	36	101	119	39	5
Sr	76	45	67	62	42	52	66	53	36	139	64	74	106	59	8	22	27	13
Ba	189	257	285	149	159	67	54	67	265	149	208	164	196	155	751	510	423	26
Th	2.30	2.00	2.10	3.18	1.78	2.85		2.56	2.27	2.20	2.12	3.26	3.48	2.59	6.25	6.85	6.19	5.28
Zr	114	110	97	113	106	162	160	148	137	144	126	109	108	205	240	224	206	163
Hf	3.10	2.80	2.90	3.37	3.05	4.62		4.08	3.68	3.63	3.39	2.82	3.29	4.99	6.78	6.41	5.94	5.14
Nb	4	4	4	5	5	6	6	5	5	6	5	4	5	7	10	11	12	9
La	8.01	6.34	6.98	9.80	6.91	11.3		7.56	7.07	5.92	8.47	9.88	8.51	13.5	18.8	25.6	21.6	18.7
Ce	18.7	16.5	17.1	23.4	17.5	27.8		19.4	17.6	14.5	20.9	22.9	21.1	34.8	45.0	61.6	54.5	47.0
Nd	9.57			13.0	10.4				12.0	9.16	13.4	11.5	11.1	23.5	24.4	33.2	30.1	
Sm	2.44	2.50	2.83	3.20	2.94	4.46		3.73	3.22	2.55	3.93	2.70	2.56	6.83	5.99	7.71	8.08	7.96
Eu	0.64	0.70	0.68	0.56	0.82	1.21		1.09	0.87	0.79	1.13	0.54	0.50	1.52	0.89	1.14	1.27	1.26
Tb	0.60	0.56	0.61	0.66	0.73	1.15		0.99	0.72	0.61	0.79	0.53	0.60	1.30	1.30	1.40	1.54	1.44
Yb	2.79	2.47	2.56	3.11	3.02	4.80		4.30	3.70	4.15	3.30	2.28	2.30	6.27	8.11	7.77	7.02	4.09
Lu	0.45	0.39	0.42	0.50	0.48	0.76		0.64	0.63	0.65	0.53	0.36	0.37	1.01	1.29	1.22	1.10	0.61
Y	24	20	23	25	23	39	37	36	31	29	29	19	18	51	55	62	56	41
Sc	9.6	11.0	9.3	6.0	8.7	10.1		7.7	10.4	10.8	9.6	14.6	14.5	9.1	7.1	7.9	7.6	5.7
V	27	15	15	11	1	1	1		2	4	15	73	63	2		1	<1	<1
Cr	7	7	5	1	1	2	1	1	1	<1	<1			1	<1	<1	<1	<1
Ni	5	7	5	1	3	2	6	4	3	1	3		20	10	4	<1	4	2
Zn	40	54	46	30	22	46	102	44	53	70	40	62	59	43	173	68	50	18

TABLE 3

Selected analyses of felsic volcanic rocks of Fourchu Group (Coastal, Coxheath and East Bay Hills blocks and Point Michaud)

	Coastal				Coxheath			East Bay				Michaud Point		
	CR-1	CR-2	CR-3	CR-4	KJ-26	KJ-27	KJ-28	EBR-1	EBR-2	EBR-3	EBR-4	M-1	M-2	M-3
wt%														
SiO_2	75.27	74.07	70.11	73.27	74.36	72.27	68.76	66.07	66.37	66.92	73.65	75.53	73.49	71.78
TiO_2	0.32	0.34	0.43	0.36	0.44	0.44	0.48	0.67	0.54	0.67	0.17	0.20	0.30	0.30
Al_2O_3	13.92	13.77	14.21	13.78	14.74	13.49	16.92	15.30	16.15	16.13	14.80	13.46	13.55	14.67
Fe_2O_3	2.24	2.99	3.59	2.38	2.64	2.60	2.50	4.00	3.68	3.90	1.53	1.15	2.12	2.47
MnO	0.12	0.10	0.14	0.10	0.02	0.05	0.03	0.07	0.07	0.09	0.03	0.04	0.14	0.08
MgO	0.42	0.57	1.61	0.52	0.81	1.08	0.68	1.64	2.06	1.18	0.24	0.28	0.75	0.72
NaO	0.89	2.35	2.98	1.63	0.28	1.64	0.90	3.66	2.50	1.96	1.42	0.32	1.69	2.48
Na_2O	6.94	4.81	4.78	5.11	3.48	2.80	5.62	3.56	2.69	6.06	4.24	5.42	4.77	4.76
K_2O	1.25	0.56	0.95	2.13	3.42	3.96	3.15	3.47	4.11	3.21	3.34	2.93	2.58	2.24
P_2O_5	0.06	0.06	0.07	0.08	0.06	0.08	0.08	0.14	0.14	0.22	0.06	0.04	0.04	0.05
LOI	0.46	0.31	0.80	0.62	0.90	1.40	1.60	2.23	2.69	1.10	1.31	0.46	0.58	0.55
Total	102.00	99.93	99.67	99.98	101.15	99.81	100.72	100.81	101.00	101.44	100.79	99.83	100.01	100.10
ppm														
Rb	17	12	18	43	116	128	99	153	201	107	116	56	27	48
Sr	114	290	433	127	103	203	145	217	206	144	58	82	169	297
Ba	372	242	432	439	499	743	477	527	549	611	151	724	770	743
Th	2.44	2.80	2.73	3.82	16.6	18.0	16.2	14.7	14.8	11.2	12.4	8.30	7.20	7.70
Zr	190	173	178	159	310	205	328	152	151	207	89	149	141	163
Hf	5.15	4.86	4.76	4.66	9.05	6.22	9.12	4.35	4.34	4.98	3.20	3.20	4.10	4.20
Nb	7	6	7	8	11	10	13	8	8	10	11	11	7	6
La	17.3	13.8	17.4	15.0	26.5	31.6	20.8	23.2	23.3	22.5	16.2	28.6	20.5	20.6
Ce	45.1	35.5	43.8	37.1	63.3	75.4	45.6	53.0	53.9	53.1	33.7	67.5	47.4	46.6
Nd	28.7	21.8	26.0	20.9	28.9	29.3	22.0	23.5	22.5	27.5	11.6	28.1	20.9	
Sm	7.84	5.84	6.80	5.23	5.89	5.95	4.98	5.06	4.51	5.78	2.73	5.03	3.86	3.44
Eu	2.06	1.54	1.86	1.35	0.94	1.02	0.97	1.14	0.89	1.36	0.56	1.02	0.97	0.92
Tb	1.60	1.17	1.37	1.00	1.06	0.93	1.04	0.72	0.58	0.86	0.32	0.71	0.61	0.47
Yb	6.44	4.80	5.52	4.31	4.40	3.41	4.45	2.45	2.09	3.51	0.81	3.28	2.86	1.98
Lu	0.97	0.78	0.82	0.70	0.68	0.51	0.69	0.37	0.34	0.52	0.11	0.52	0.47	0.33
Y	55	42	44	37	36	32	42	25	22	33	12	31	26	20
Sc	13.5	12.9	15.7	10.6	7.4	7.5	7.6	9.7	9.4	10.6	3.0	3.2	5.5	5.2
V	1	7	18	13	33	39	23		99	68	16	11	18	35
Cr	1	2	9	1	1	15	3	13	31	2	2	3	20	13
Ni	6	6	8	6	11	17	8	15	24	10	5	4	4	2
Zn	39	37	62	36	41	37	42	48	53	70	33	25	231	33

Rocks of Coastal and Coxheath blocks—lavas and sheets; rocks of East Bay Hills block and Michaud Point—tuffs; Some trace element data in samples CR-1, CR-2 and CR-4 were taken from Kennedy (1985). Some trace elements in sample M-1 were taken from Cameron (1985); and both major and some trace elements in samples KJ-26, KJ-27 and KJ-28 were taken from Jones (1987).

range of 58 to 68% occur in subordinate amounts or are pyroclastics.

Alteration

The felsic volcanic rocks of the Fourchu Group were affected by secondary alteration which, in some samples, led to redistribution, particularly of K, Na and related trace elements. In the wider vicinity of the Stirling deposit, some felsic rocks display pronounced mineralogical and chemical changes. Several mineralogically distinct types of alteration can be recognized: sericitization, albitization, carbonatization, chloritization, and silicification. Some of these different types of alteration may be found together in the same location and sample, and thus no simple zonal alteration pattern is apparent. Compositional changes in the felsic rocks caused by alteration can be estimated by comparison with the average of a set of least altered rhyolites of the Stirling block (Table 1) or, in the case of pyroclastic rocks of the Stirling block from St.Esprit with a relatively unaltered sample (2-447, Table 2).

The strongly albitized samples (e.g. 3-587, Table 2) are enriched in Na_2O and depleted in CaO, K_2O, Rb and Ba. It is possible that the albitization also led to an enrichment of heavy REE (HREE) (sample 2-325, Fig. 2, Table 2). The carbonatization produced an enrichment in CaO and LOI (sample 1-54, Table 2). It appears that the abundances of Mg, Ni, Cr and Sc might have also been enhanced. Distinct enrichment in MgO (up to 5%) and probably some depletion in K_2O and Rb are the result of chloritization (e.g. sample 3-570, Table 2). Two distinctly sericitized pyroclastic samples (2-336 and 2-417) display an enrichment in K which appears to be associated with an increase of Rb, Ba and Mg and decrease in Na and Sr. These two tuffs are also enriched in HREE relative to the least altered sample 2-447 (Fig. 3). The silicified pyroclastic sample (2-457) shows a decrease in Al, Fe, K, Rb and Ba. In addition, a SiO_2 enrichment may be associated with a decrease of HREE resulting in higher La/Yb ratios (Fig. 3). However, in a large majority of the Fourchu Group rocks, high-field-strength-elements (HFSE) and REE, which are usually considered to be resistant to alteration/metamorphic processes, do not appear to be significantly affected. Their relative immobility during secondary modification is suggested by similarities to the fresh volcanic rocks (Ewart, 1979) as well as to some typical Archean felsic metavolcanic rocks (Lesher et al., 1986).

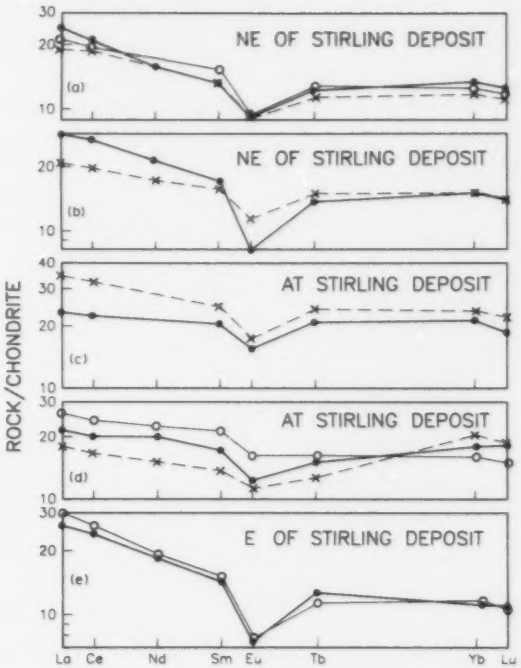

Fig. 2. Chondrite-normalized REE abundances in the rhyolitic rocks from the Stirling block. (a) Samples collected about 4 km northeast of the mine site: 4-120 (●), 4-289 (×) and 4-345 (○); (b) samples from about 2 km northeast of the mine site: 3-293 (●) and 3-400 (×); (c) samples collected near the mine site: 3-359 (×) and 3-587 (●); (d) samples from the vicinity of the mine site: 2-270 (●), 2-325 (×) and 2-386 (○); (e) samples collected about 1.5 km east of the mine site: 1-54 (○) and 1-113 (●).

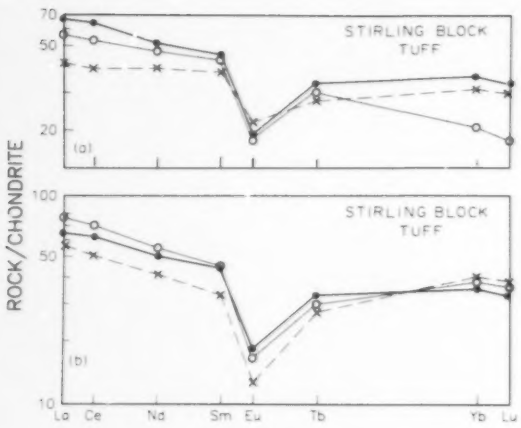

Fig. 3. Chondrite-normalized REE abundances in the felsic pyroclastic rocks of the Stirling block from St. Esprit. (a) 2-170 (×), 2-447 (●) and 2-457 (○); (b) 2-336 (×), 2-417 (○) and 2-447 (●).

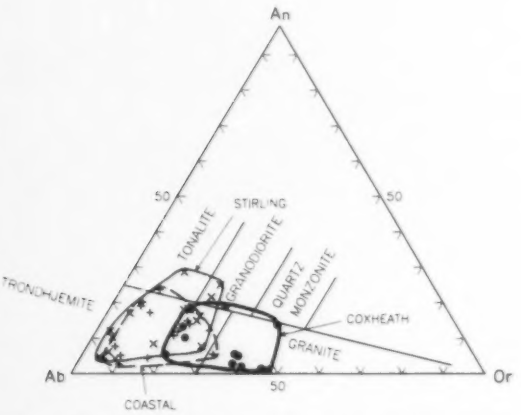

Fig. 4. Plot of normative anorthite (An), albite (Ab) and orthoclase (Or) for the rhyolitic rocks of the Coastal (+), Stirling (×) and Coxheath (●) blocks showing compositional fields of some siliceous plutonic rocks (after O'Connor, 1965).

Stirling block

In the Stirling block, most felsic rocks are rhyolitic in composition with SiO_2 contents between 68 and 79%. The rhyolites fall predominantly into the trondhjemitic field on a normative feldspar diagram (Fig. 4) and into the field of the low-K rhyolites on the K_2O vs SiO_2 graph (Fig. 5a). The distributions of Y-Nb and Rb-(Y+Nb) (Pearce et al., 1984) is indicative of a magmatic arc setting (Fig. 6). The rocks have low abundances of incompatible trace elements such as Sr, Ba, La, Zr (Fig. 5b) and Th (Table 1). Their mantle-normalized incompatible element pattern (Fig. 7) displays a moderate enrichment of K, Rb, Ba and Th relative to HFSE and HREE which is accompanied by low La/Yb, Th/Yb, Th/Hf and La/Zr ratios, features that resemble tholeiitic/low-K rhyolites of the volcanic arcs (e.g., Ewart, 1979; Gill and Stork, 1979).

The distribution of incompatible trace elements, particularly REE and HFSE, in these rhyolites is also comparable to that of the FIIIa felsic metavolcanic rocks of Lesher et al. (1986) which host major base-metal sulphide deposits. The Stirling rhyolites are characterized by a relatively flat REE pattern with a negative Eu anomaly, $(La/Yb)_n$ (n=chondrite-normalized) usually between 1 and 2, and $(La/Sm)_n$ is between 1.1 and 1.8 (Fig. 2). The rocks have a low Zr/Y ratio (3.5 to 6.2), and moderate abundances of Sc (~6–15 ppm). Negative Eu and Sr anomalies (Fig. 7) accompanied by low contents of Al_2O_3 can be attributed mainly to feldspar fractionation (Lesher et al., 1986; Lesher and Campbell, 1987).

Coastal block

The felsic rocks of the Coastal block are mostly rhyolites with SiO_2 in the range of 69–77% and Al_2O_3 varying between 12.4 and 15.9%. Exceptions are silicified samples that are strongly enriched in SiO_2 (~82%) and have < 10% Al_2O_3. The Coastal block rhyolites have high Na_2O/K_2O ratios, usually > 2. On the normative An–Ab–Or graph (Fig. 4), the rocks plot into the trondhjemite field whereas on the K_2O vs SiO_2 diagram, they straddle the boundary between low-K and calc-alkalic rhyolites (Fig. 5). The relationship among Rb, Nb and Y indicates that the felsic rocks have vol-

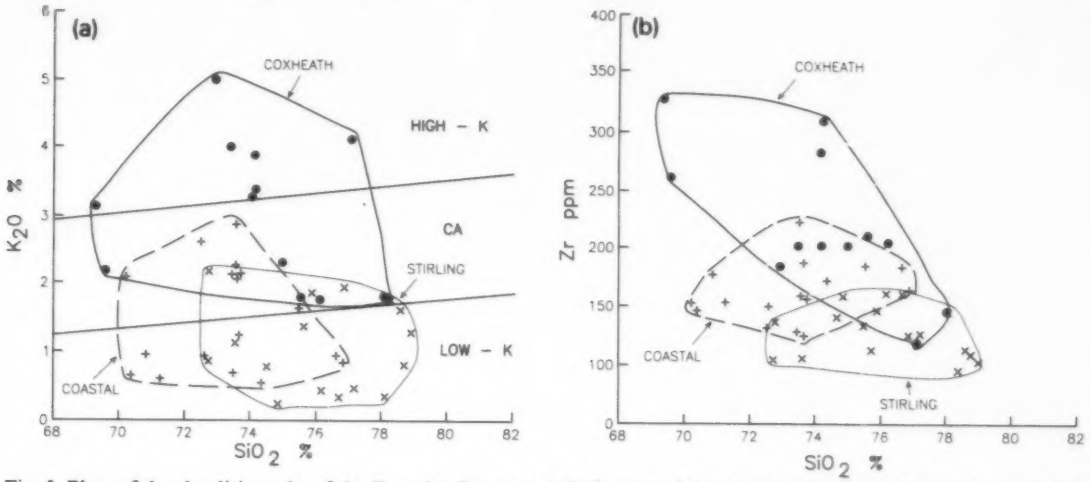

Fig. 5. Plots of the rhyolitic rocks of the Fourchu Group: (a) K_2O versus SiO_2 showing the fields for low-K, calc-alkalic (*CA*) and high-K rhyolites (after Ewart, 1979); (b) Zr versus SiO_2. Symbols as in Fig. 4.

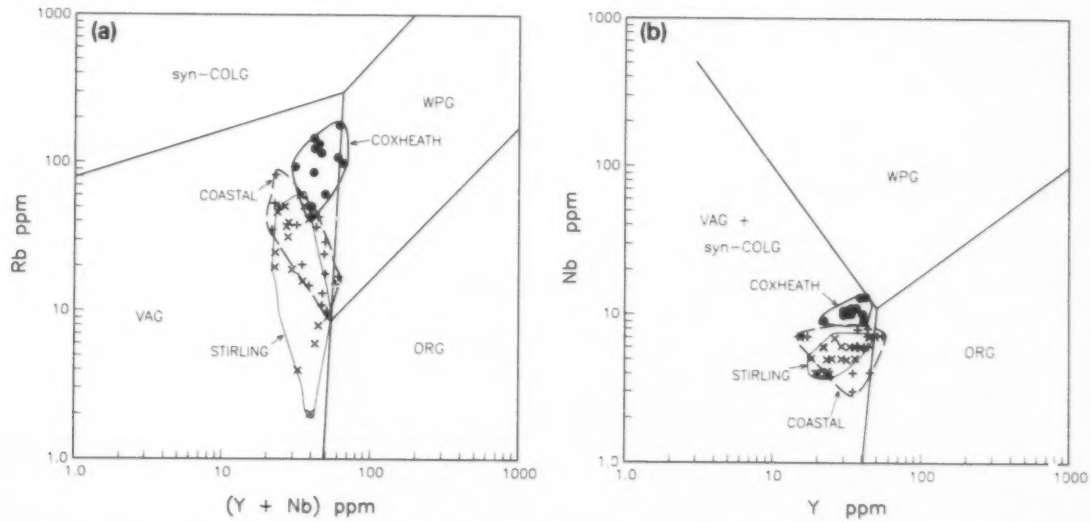

Fig. 6. Plots of rhyolitic rocks of the Fourchu Group: (a) Rb–(Y+Nb) discrimination diagram of Pearce et al. (1984); (b) Nb–Y discrimination diagram of Pearce et al. (1984). *WPG*=within-plate granites, *ORG*=ocean ridge granites, *VAG*=volcanic arc granites, and *syn-COLG*=syn-collision granites. Symbols as in Fig. 4.

canic arc affinities (Fig. 6). Compared to the rhyolites from the Stirling block, the Coastal block rhyolites are higher in Al, Na, Sr and most of the other incompatible trace elements (Table 1, Figs. 5b and 7). However, their mantle-normalized trace element pattern (Fig. 7) is relatively flat with only a small enrichment of K, Rb, Ba and Th relative to HFSE and HREE and exhibits significantly smaller negative anomalies of Eu and Sr than that of the Stirling block rhyolites.

Although abundances of REE are mostly higher in the Coastal rhyolites, both the Stirling and Coastal block rhyolites have similar

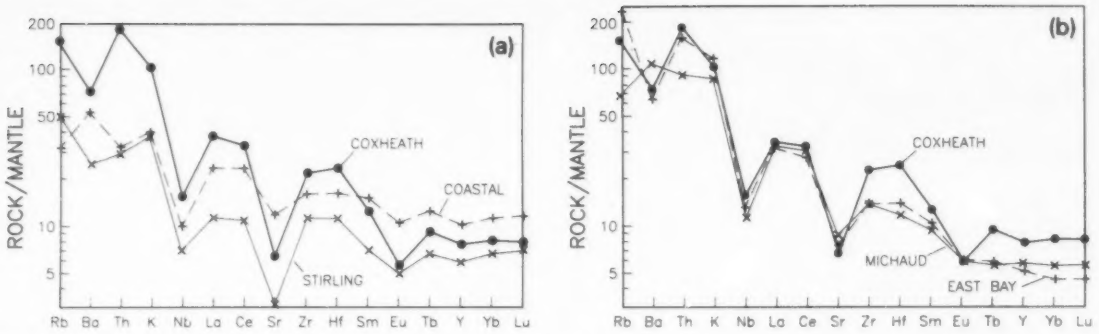

Fig. 7. Mantle-normalized incompatible element patterns of the averages of (a) the least-altered rhyolitic rocks of the Coastal, Stirling and Coxheath blocks, and (b) the felsic pyroclastic rocks from the East Bay Hills block and Michaud Point. Normalizing values after Sun and McDonough (1989).

La/Yb ratios. The chondrite-normalized REE patterns of the Coastal rhyolites are slightly enriched in light REE (LREE), have unfractionated HREE and display a small negative Eu anomaly (Fig. 8a). Their $(La/Yb)_n$ ratio ranges between 1.5 and 2.1, and the $(La/Sm)_n$ ratio is between 1.2 and 1.6. The sub-parallel REE patterns of the rhyolites suggest that some compositional variations are due to fractional crystallization.

In general, the trace element geochemistry of the Coastal block rhyolites is similar to that of the low-K/tholeiitic rhyolites from the Stirling block (Fig. 7) and recent volcanic arc suites (Ewart, 1979). They also resembles the Archean FIII felsic metavolcanic rocks of Lesher et al. (1986), although they have relatively small negative Eu and Sr anomalies. The smaller negative Eu and Sr anomalies accompanied by higher Al_2O_3 abundances (Table 1) in the Coastal block rhyolites compared to those of the Stirling block, suggest that these rocks underwent less extensive feldspar fractional crystallization.

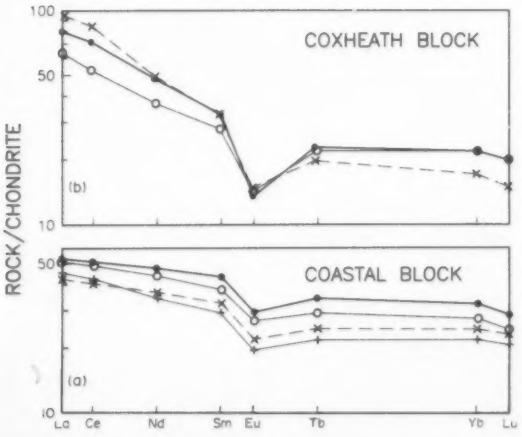

Fig. 8. Chondrite-normalized REE abundances in the rhyolitic rocks of (b) the Coxheath: KJ-26 (●), KJ-27 (×) and KJ-28 (○); and (a) Coastal blocks: CR-1 (●), CR-2 (○), CR-3 (×) and CR-4 (+).

Coxheath block

The felsic rocks generally have SiO_2 contents between 69 and 78% and $Al_2O_3 > 12\%$. Their normative feldspar compositions plot into granitic and trondhjemitic fields (Fig. 4). The Na/K ratio of the Coxheath rhyolites is much lower than in the rhyolites from the Coastal and Stirling blocks. According to their major element composition, the felsic rocks are calc-alkalic and straddle the boundary between calc-alkalic and high-K rhyolite fields in the K_2O vs SiO_2 diagram (Fig. 5). In terms of the Y–Nb and Rb–(Nb+Y) distribution, the rocks have volcanic arc affinities (Fig. 6). The REE patterns of the Coxheath rhyolites are distinctly enriched in LREE and depleted in Eu (Fig. 8b). Their $(La/Yb)_n$ ratio ranges be-

tween 2.8 and 5.6 whereas the $(La/Sm)_n$ ratio is around 2.5.

Compared to Coastal and Stirling rhyolites, the felsic volcanic rocks of the Coxheath block are higher in K and strongly incompatible trace elements (Table 1, Figs. 5 and 7) such as Rb, LREE and Th. In addition, their mantle-normalized pattern (Fig. 7) is more fractionated with a larger enrichment of the strongly incompatible elements relative to HFSE and HREE. The contrasting characteristics are also indicated by higher La/Yb, Zr/Y, Th/La, Th/Hf and Th/Yb ratios but lower Sc abundances (Table 1). The distribution of incompatible trace elements is typical of calc-alkalic rocks from volcanic arcs (Ewart, 1979), and resembles the group FII felsic metavolcanic rocks from the greenstone belts of the Canadian Shield (Lesher et al., 1986).

Pyroclastic rocks

The felsic tuffs, with minor amounts of foreign material, from the East Bay Hills block and Michaud Point (Table 3) have ~66–75% SiO_2 and relatively high contents of K_2O. They resemble the rhyolites of the Coxheath block (Table 1) and recent calc-alkalic rhyolitic rocks (Ewart, 1979). Compared to the rhyolites of the Coastal and Stirling blocks, they have lower Na_2O/K_2O and K/Rb (~230) ratios. Their REE patterns are enriched in LREE and are similar to those of the Coxheath rhyolites but lack a distinct negative Eu anomaly (Fig. 9). The mantle-normalized pattern (Fig. 7) shows that the East Bay Hills and Michaud Point volcanics also have lower abundances of HFSE and HREE than the Coxheath rhyolites and a less pronounced negative Sr anomaly. The distribution of immobile incompatible trace elements in these rocks (Fig. 7) is similar to that of the recent calc-alkalic rhyolitic rocks (Ewart, 1979) and their Archean equivalents (Condie, 1981; Lesher et al., 1986).

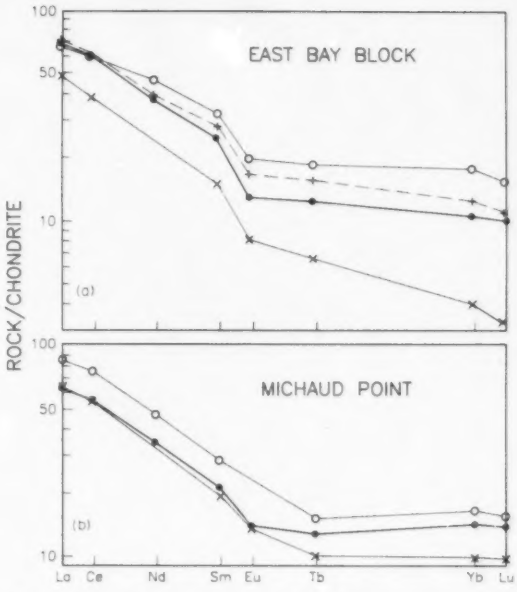

Fig. 9. Chondrite-normalized REE abundances in the felsic pyroclastic rocks of (a) the East Bay Hills block: EBR-1 (+), EBR-2 (●), EBR-3 (○) and EBR-4 (×); and (b) Michaud Point: M-1 (○), M-2 (●) and M-3 (×)

Discussion

Petrogenesis

The two most frequently invoked models for the genesis of the large volume of rhyolitic magma are (1) fractional crystallization from a basaltic precursor, and (2) melting of the crust in which rising basalts provide the heat necessary to cause melting in the crust (Barker, 1981). More complex petrogenetic models involving both mantle and crustal sources have also been proposed (Barker, 1981; Hildreth, 1981). The relative role of these processes in the genesis of the Fourchu felsic rocks will be evaluated in turn.

Fractionation from a basaltic precursor

Rhyolitic rocks of the Fourchu Group display distinct differences in their trace element composition. The rhyolites from the Coastal and Stirling blocks have abundances of incom-

patible trace elements characteristic of tholeiitic/low-K rocks whereas the felsic rocks of the Coxheath block are similar to modern calc-alkalic rhyolites of orogenic regimes. These compositional differences include the shapes of the REE patterns and the ratios of $(La/Yb)_n$, $(La/Sm)_n$, Zr/Y, Zr/Sm, Th/Yb, Th/La, K/Rb and Y/Nb. These contrasting ratios are not readily modified by fractionation of common rock-forming minerals. Thus, the calc-alkalic and low-K/tholeiitic rhyolites could not have been derived from a single parental magma by fractional crystallization of major mineral phases in the rhyolites. Fractionation of accessory apatite (Harrison and Watson, 1984), which might qualitatively explain some differences in REE patterns, is not consistent with the variations of P in the rhyolites. Similarly, it may be concluded that partial melting of a single source involving the same mineral assemblages cannot account for the compositional range of the rhyolites. However, the similarities of the geological setting as well as their association in time and space suggest that the rhyolitic rocks of the individual blocks were produced by similar processes. Some compositional characteristics and differences (including low-K vs calc-alkalic) of the rhyolites are similar to those of the associated basalts. The flat or slightly LREE-enriched patterns of the volcanic arc tholeiitic basalts of the Coastal and Stirling blocks (Fig. 10) are broadly comparable to the patterns of the accompanying rhyolites. Likewise, the sloping REE patterns of the Coxheath and East Bay Hills felsic volcanic rocks resemble those of the associated arc basalts (Fig. 10). Such compositional similarities in the individual blocks of the Fourchu Group suggest a genetic relationship between the basalts and rhyolites, probably in part through a crystal–liquid fractionation process. However, quantitatively, a simple fractionation model alone cannot explain the distribution of the incompatible trace elements, for the following reasons: (a) the relatively low abundances of these elements in the rhyolites, particularly of Stirling and Coastal blocks suggest that the rhyolitic rocks are not strongly differentiated as would be expected of the products of extensive fractional crystallization, and (b) the differences in the ratios of incompatible trace elements between the rhyolites and basalts of individual blocks.

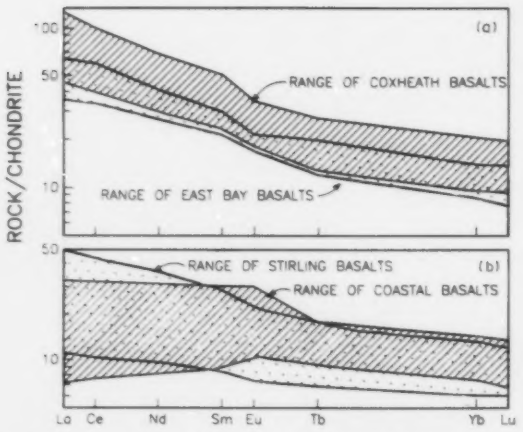

Fig. 10. Ranges of chondrite-normalized REE abundances for the basaltic rocks of the individual blocks of the Fourchu Group (after Dostal et al., 1990).

The small amount of intermediate rocks in the volcanic sequences points to the silica gap among the mafic and felsic rocks which, together with the lack of recognizable cumulate rocks, suggests that the silicic rocks were neither derived by closed system fractional crystallization from a basalt parent, nor by a process involving continuous differentiation and crustal contamination of a basalt precursor. Furthermore, the abundances of the incompatible trace elements in the subordinate andesites and related intermediate rocks are frequently higher than those of the rhyolites, arguing against an origin of the silicic rocks by simple fractional crystallization of the andesites.

Although both mafic and felsic rocks were affected by crustal contamination, the combination of fractional crystallization of basaltic magma and assimilation of typical crust was probably not the main process of generating the

felsic volcanic rocks of the Stirling and Coastal blocks. Typical crustal rocks are enriched in LREE. Thus a combination of crystal fractionation of the basalts and assimilation of either typical crustal rocks or their low melting fraction (DePaolo, 1981) cannot account for the rather flat REE patterns of the low-K rhyolites. Also, since most of the Stirling rhyolites have lower La/Yb ratios and flatter REE patterns than the basalts, the crustal contaminant would have to have a rather unusual REE composition with LREE depleted patterns. Likewise, the high K/Rb ratios in the rhyolitic rocks of the Coastal and Stirling blocks are significantly higher than those of typical upper crust (Taylor and McLennan, 1985), suggesting that an upper crustal contaminant did not play an important role in their genesis.

Partial melting of crust

The alternative model for the origin of the rhyolites of the Fourchu Group involves partial melting of a heterogeneous crust with subsequent differentiation. The rather flat REE patterns of the low-K rhyolites of the Coastal and Stirling blocks place constraints on the composition of their source. The relatively high contents of Yb and Y, the flat unfractionated heavy REE segment of the pattern and the low La/Yb ratio, indicate that the melts originated from a garnet-free source, probably either gabbro/basic granulite or amphibolite. Numerous experimental studies (e.g. Stern et al., 1975; Helz, 1976; Spulberg and Rutherford, 1983) indicate that the melting of basalts with gabbroic or amphibolitic assemblages can produce silicic liquids. The source probably had a flat or LREE depleted pattern because moderate and high degrees of partial melting (> 10–15%) involving only feldspars, pyroxenes and amphibole produce melts with REE patterns that do not differ drastically from the pattern of the source. To test the partial melting process for the generation of the acid magma from a mafic parent, the model calculation for REE are shown in Fig. 11a. The average Archean

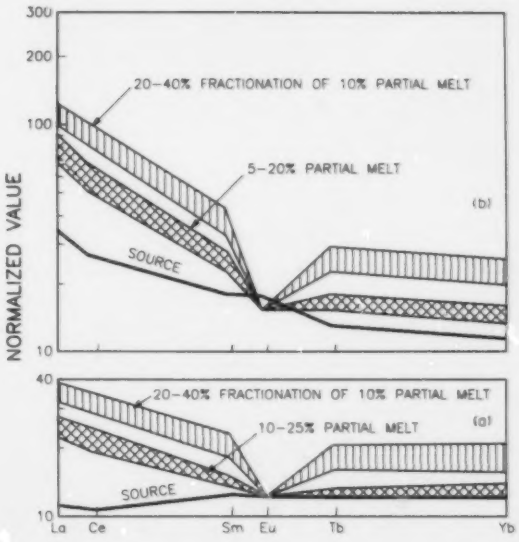

Fig. 11. (a) Melting model for the generation of the REE patterns of the rhyolitic rocks of the Coastal and Stirling blocks. The cross-hatched area is calculated chondrite-normalized REE patterns of the melts produced by batch melting of an average of Archean mafic rocks (Taylor and McLennan, 1985). The degree of melting (F) ranges from 10 to 25%. The phase proportions in the original source (X) and melts (P) are from Nicollet et al. (1979); Amphibole (X, P) 0.5 and 0.2, plagioclase 0.4 and 0.8, clinopyroxene 0.1 and 0.0. The partition coefficients selected by Rudnick and Taylor (1986) and Arth (1976) were used. Single hatched area is calculated REE abundances in the liquids produced by 20 and 40% fractional crystallization of feldspars (plagioclase:K-feldspar = 9:1) from the 10% partial melts. The partition coefficients used are the same as for the melting model. (b) The chondrite-normalized REE abundances in melts produced by partial (batch) melting of a amphibolite-facies crustal rock with REE content of an average of the lower crust of Taylor and McLennan (1985). The degree of melting (F) ranges from 5 to 20% (cross-hatched area). Mineral proportions of the source (X) as well as melting proportions (P) are modified after Stern and Gottfried (1986) and Cleverly et al. (1986). Phases and their values for X and P are: amphibole 0.4 and 0.0, plagioclase 0.5 and 0.5, K-feldspar 0.05 and 0.25 and quartz 0.05 and 0.25. Single hatched area is calculated REE abundances in the liquids produced by fractional crystallization of 20% and 40% feldspars (plagioclase:K-feldspar = 1:1) from the 5% partial melt. The partition coefficients selected by Rudnick and Taylor (1986) and Arth (1976) were used.

mafic volcanic rock of Taylor and McLennan (1985) was used as the source composition. This average for REE is similar to the REE abundances in typical island arc tholeiitic basalts.

Model calculations indicate that 10–25% of melting of Archean mafic rocks composed largely of plagioclase, pyroxene and/or amphibole, could account for the geochemical characteristics of the rhyolites. Such felsic melts have subsequently been modified by fractional crystallization and crustal contamination during their ascent to the surface. Fractional crystallization involving feldspars would enhance a negative Eu anomaly in the melts (Fig. 11a).

The shape of the REE patterns of the Coxheath rhyolites suggests their generation from a source with a distinct LREE enrichment. The calc-alkalic mafic rocks of the Coxheath and East Bay Hills blocks were emplaced on a continental crust in a volcanic arc setting (Dostal et al., 1990). Thus, anatexis of the lower part of the continental crust can be invoked for the origin of the calc-alkalic felsic melts. Currie (1987) argued that the lower crust under Cape Breton Island is formed by granulites with a composition of intermediate volcanic rocks. Phase assemblages for mafic and intermediate rocks of the lower crust probably include garnet, pyroxenes and amphibole in addition to feldspars and quartz. Flattish heavy REE patterns and high Y and Yb abundances argue against the role of garnet in the genesis of these rocks. Figure 11b shows the results of a model calculation of the melting of garnet-free granulite or amphibolite facies crust assuming that the source has REE abundances of the average lower crust of Taylor and McLennan (1985). The REE patterns of the Coxheath rhyolites can be modelled closely by partial melting of garnet-free granulite- or amphibolite-facies rocks with a composition of the average lower crust. The felsic magma subsequently underwent fractional crystallization of a feldspar-dominated assemblage which led to an increase of the total abundances of REE and of the negative Eu anomaly. A similar process can be invoked for the origin of felsic volcanic rocks of Michaud Point and the East Bay Hills.

The variations in ratios such as Th/La, K/Rb, K/La and Ba/Rb in all rhyolitic suites indicate the role of crustal contamination in the genesis of the rhyolitic rocks, particularly from the Coxheath block. The Th/La ratio, which is frequently considered as a sensitive indicator of crustal contamination, has high values in the rhyolites suggesting the addition of an upper crustal component. However, this process is probably only of secondary importance in generating the differences between the rhyolitic rocks of the various blocks.

Trace-element geochemistry and massive sulphide deposits

Lesher et al. (1986) have argued that the primary magmatic distribution of the REE in the felsic metavolcanic rocks of the Superior Province of the Canadian Shield can be used in exploration for volcanogenic massive sulphide deposits. They documented that most massive base-metal deposits are associated with felsic metavolcanic rocks that are characterized by relatively flat REE patterns with a negative Eu anomaly (type FIII). The rhyolitic rocks with sloping REE patterns (types FI and FII) are mostly barren, particularly when they do not have a negative Eu anomaly. The Fourchu Group rhyolites are within the range of the Archean felsic metavolcanic rocks of the Superior Province. The felsic volcanic rocks of the Coxheath, East Bay Hills and Michaud Point blocks are similar to the calc-alkalic lavas of type FII, whereas the felsic metavolcanic rocks of the Coastal and Stirling blocks resemble the rocks of the FIII type of Lesher et al. (1986). Compared to typical FIII rhyolites associated with massive sulphide deposits and to the deposit-bearing Stirling felsic rocks, the Coastal block rhyolites do not display pronounced negative Eu and Sr anomalies (Fig. 7) and have relatively high contents of Al_2O_3

(Table 1; Figs. 7 and 8). The differences in magnitude of the negative Eu and Sr anomalies and the contents of Al_2O_3 between the Stirling and Coastal rhyolites support the conclusion of Lesher et al.(1986) that extensive feldspar-dominated crystal fractionation in a high-level subvolcanic magma chamber is an essential element of the ore-forming hydrothermal process. The subvolcanic magma chamber is usually interpreted to provide heat to drive the ore-forming hydrothermal system (Lesher et al., 1986). Close similarities of the trace element characteristics of the Stirling block rhyolites to those of the ore-bearing FIII type of Lesher et al. (1986) suggest that the base-metal sulphide deposits of Late Proterozoic age may also be preferentially associated with low-K felsic rocks which have relatively flat REE patterns and distinct negative Eu and Sr anomalies. These trace-element characteristics of the felsic metavolcanic rocks can be used to identify a promising environment for massive sulphide deposits. The Coxheath calc-alkalic rhyolites also have negative Eu and Sr anomalies but show an inclined REE pattern. Although mineralization has been recorded in the volcanic rocks of Coxheath block, to date no economic mineralization has been discovered.

Conclusions

The Late Proterozoic felsic volcanic rocks of the Fourchu Group display significant compositional variations. The rocks of the Coastal and Stirling blocks are mainly low-K/tholeiitic rhyolites with flattish REE patterns. These felsic rocks, emplaced on a transition between oceanic and continental crust, may be derived by partial melting of a basement composed predominantly of mafic igneous rocks similar to recent island arc tholeiites or tholeiitic basalts of Precambrian greenstone belts. Although both suites underwent fractional crystallization, the Stirling rhyolites display pronounced negative Eu and Sr anomalies suggesting that the process was dominated by feldspar fractionation and probably took place in a high-level subvolcanic magma chamber.

The Coxheath, East Bay Hills and Michaud Point felsic volcanic rocks, emplaced on the continental crust, resemble recent calc-alkalic rhyolites of the orogenic continental margins. Their REE patterns display a gentle negative slope with a moderate negative Eu anomaly in the Coxheath block. The rocks were derived by partial melting of common lower crustal rocks and subsequently underwent fractional crystallization.

The enhancement of trace elements strongly enriched in an upper crust is expressed by high element ratios, such as Th/La, and suggests that fractional crystallization in all the rhyolitic suites was accompanied by assimilation of crustal material. Although the felsic volcanic rocks of the Fourchu Group do not appear to be directly fractionated from the mafic rocks, the similarities in their incompatible element profiles suggest that they are genetically related. In addition, mafic magma probably provided heat for melting. Extensive lower crustal melting that produced the parental magma of the rhyolites was facilitated by the intrusion of mantle-derived basaltic magma into the hot crust (Huppert and Sparks, 1988).

Trace element characteristics of the Stirling block rhyolites that host the massive sulphide deposit, are closely comparable to the felsic metavolcanic rocks of FIII type of Lesher et al. (1986) from the Superior Province of the Canadian Shield that are preferentially associated with massive sulphide mineralization. The similarities suggest that the low-K/tholeiitic felsic volcanic rocks with flattish REE patterns, that display distinct negative Eu and Sr anomalies, are indicators of a promising environment for massive base-metal mineralization even outside of the Superior Province of the Canadian Shield, in volcanic belts at least as young as Late Proterozoic.

Acknowledgements

This study was supported by the Natural Sciences and Engineering Research Council of Canada (operating grant A3782) and by the Nova Scotia Department of Mines and Energy (under the Canada-Nova Scotia Mineral Development Agreement). Permission to publish was granted by the Minister of the Nova Scotia Department of Mines and Energy.

References

Arth, J.G., 1976. Behavior of trace elements during magmatic processes—A summary of theoretical models and their applications. J. Res. U.S. Geol. Surv., 4: 41–47.

Barker, F., 1981. Introduction to Special Issue on granites and rhyolites: A commentary for the nonspecialist. J. Geophys. Res., 86: 10131–10135.

Barr, S.M., MacDonald, A.S. and White, C.E., 1989. Geological maps of the Coastal and Stirling belts, southeastern Cape Breton Island, Nova Scotia. Geol. Surv. Can. Open File Rep. 1988.

Barr, S.M., Bevier, M.L., MacDonald, A.S. and White, C.E., 1990. Complex volcanic history confirmed for southeastern Cape Breton Island. N.S. Dept. Mines and Energy Report 90-3, 35 pp.

Cameron, J.G., 1985. Petrography and geochemistry of the volcanic rocks of the Stirling Belt near Point Michaud, Richmond County, Cape Breton Island, Nova Scotia. B.Sc. Thesis, St. Mary's University, Halifax, N.S.

Campbell, I.H., Coad, P., Franklin, J.M., Gorton, M.P., Scott, S.D., Sowa, J. and Thurston, P.C., 1982. Rare earth elements in volcanic rocks associated with Cu-Zn massive sulphide mineralization: a preliminary report. Can. J. Earth Sci., 18: 619–623.

Campbell, I.H., Lesher, C.M., Coad, P., Franklin, J.M., Gorton, M.P. and Thurston, P.C., 1984. Rare-earth element mobility in alteration pipes below massive Cu–Zn–sulphide deposits. Chem. Geol., 45: 181–202.

Cleverly, R.W., Betton, P.J. and Bristow, J.W., 1986. Geochemistry and petrogenesis of the Lebombo rhyolites. In: A.J. Erlank (Editor), Petrogenesis of the Volcanic Rocks of the Karoo Province. Spec. Publ. Geol. Soc. S. Afr., 13: 171–194.

Condie, K.C., 1981. Archean Greenstone Belts. Elsevier, New York, 434 pp.

Currie, K.L., 1987. Relations between metamorphism and magmatism near Cheticamp, Cape Breton Island, Nova Scotia. Geol. Surv. Can. Pap., 85-23: 66 pp.

DePaolo, D.J. 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. Earth Planet. Sci. Lett., 53: 189–202.

Dostal, J., Keppie, J.D. and Murphy, J.B., 1990. Geochemistry of Late Proterozoic basaltic rocks from southeastern Cape Breton Island, Nova Scotia. Can. J. Earth Sci., 23: 619–631.

Ewart, A., 1979. A review of the mineralogy and chemistry of Tertiary dacitic, rhyolitic and related salic volcanic rocks. In: F. Barker (Editor), Trondhjemites, Dacites and Related Rocks. Elsevier, Amsterdam, pp. 13–122.

Gill, J.B. and Stork, A.L. 1979. Miocene low-K dacites and trondhjemites of Fiji. In: F. Barker (Editor), Trondhjemites, Dacites and Related Rocks. Elsevier, Amsterdam, pp. 629–649.

Harrison, T.M. and Watson, E.B., 1984. The behavior of apatite during crustal anatexis: equilibrium and kinetic considerations. Geochim. Cosmochim. Acta, 48: 1467–1477.

Helz, R.T., 1976. Phase relations of basalts in their melting ranges at $P_{H_2O} = 5$ kb. Part II. Melt Compositions. J. Petrol., 17: 139–193.

Hildreth, W., 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism. J. Geophys. Res., 86: 10153–10192.

Huppert, H.E. and Sparks, R.S.J., 1988. The generation of granitic magmas by intrusion of basalt into continental crust. J. Petrol., 29: 599–624.

Jones, K., 1987. The petrography and geochemistry of volcanic rocks from the Coxheath Hills in southeastern Cape Breton Island, Nova Scotia. B.Sc. Thesis, St.Mary's University, Halifax, N.S.

Kennedy, S., 1985. Petrography and geochemistry of volcanic rocks of the Fourchu Group from Gabarus Bay, Cape Breton Island. B.Sc. Thesis, St.Mary's University, Halifax, N.S.

Keppie, J.D., 1989. Northern Appalachian terranes and their accretionary history. Geol. Soc. Am. Spec. Pap., 230: 159–192.

Keppie, J.D., Dallmeyer, R.D. and Murphy, J.B., 1990. Tectonic implications of $^{40}Ar/^{39}Ar$ hornblende ages from late Proterozoic-Cambrian plutons in the Avalon Composite Terrane, Nova Scotia. Geol. Soc. Am. Bull., 102: 516–528.

Lesher, C.M. and Campbell, I.H., 1987. Trace-element geochemistry of ore-associated and barren, felsic metavolcanic rocks in the Superior Province, Canada: Reply. Can. J. Earth Sci., 24: 1500–1501.

Lesher, C.M., Goodwin, A.M., Campbell, I.H. and Gorton, M.P., 1986. Trace-element geochemistry of ore-associated and barren, felsic metavolcanic rocks in the Superior Province, Canada. Can. J. Earth Sci., 23: 222–237.

Miller, C.K., 1979. The geologic setting and environment of ore deposition at the Mindamar Mine, Stirling, Richmond County, Nova Scotia. M.Sc. Thesis, Dalhousie University, Halifax, N.S., 223 pp.

Nicollet, C., Leyreloup, A. and Dupuy, C., 1979. Petrogenesis of high pressure trondhjemitic layers in eclo-

gites and amphibolites from southern Massif Central, France. In: F.Barker (Editor), Trondhjemites, Dacites and Related Rocks. Elsevier, Amsterdam, pp. 435–463.

O'Connor, J.T., 1965. A classification for quartz-rich igneous rocks based on feldspar ratios. U.S. Geol. Surv. Prof. Pap., 525-B: 79–84.

Pearce, J.A., Harris, N.B. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol., 25: 956–983.

Richardson, P.W., 1953. Some geological aspects of the Mindamar Mine, Stirling, Richmond County, N.S. CIM Bull., 46: 368–370.

Rudnick, R.L. and Taylor, S.R., 1986. Geochemical constraints on the origin of Archaean tonalitic-trondhjemitic rocks and implications for lower crustal composition. In: J.B.Dawson, D.A. Carswell, J. Hall and K.H. Wedepohl (Editors), The Nature of the Lower Continental Crust. Geol. Soc. Spec., Publ. 24: 179–191.

Spulberg, S.D. and Rutherford, M.J., 1983. The origin of rhyolite and plagiogranite in oceanic crust: an experimental study. J. Petrol., 24: 1–25.

Stern, C.R., Huang, W. and Wyllie, P.J. 1975. Basalt–andesite–rhyolite–H_2O: crystallization intervals with excess H_2O and H_2O-undersaturated liquidus surfaces to 35 kilobars, with implications for magma genesis. Earth Planet. Sci. Lett., 28: 189–196.

Stern, R.J. and Gottfried, D., 1986. Petrogenesis of a Late Precambrian (575–600 Ma) bimodal suite in Northeast Africa. Contrib. Mineral. Petrol., 92: 492–501.

Strong, D.F., 1984. Rare earth elements in volcanic rocks of the Buchans area, Newfoundlnad. Can. Jour. Earth Sci., 21: 775–780.

Sun, S.S. and McDonougl., W.F., 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In: A.D. Saunders and M.J. Norry (Editors), Magmatism in the Oceanic Basins. Geol. Soc. Spec. Publ., 42: pp. 313–345.

Taylor, S.R. and McLennan, S.M., 1985. The Continental Crust: Its Composition and Evolution. Blackwell, Oxford, 312 pp.

Watson, K.D., 1954. Paragenesis of the zinc–lead–copper deposits at the Mindamar Mine, Nova Scotia. Econ. Geol., 49: 389–412.

Weeks, L.J., 1954. Southeast Cape Breton Island, Nova Scotia. Geol. Surv. Can. Mem., 277: 112 pp.